

# Photorecombination of berylliumlike $\text{Ti}^{18+}$ : Hyperfine quenching of dielectronic resonances

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**Abstract.** The photorecombination spectrum of  $^{48}\text{Ti}^{18+}$  was measured employing the merged electron-ion beams technique at a heavy-ion storage ring. The experimental electron-ion collision energy range 0–80 eV comprises all dielectronic recombination (DR) resonances associated with  $2s \rightarrow 2p$  ( $\Delta N = 0$ ) core excitations as well as trielectronic recombination (TR) resonances that involve  $2s^2 \rightarrow 2p^2$  core double-excitations. At low collision energies DR resonances are observed that are associated with the excitation of metastable  $2s\,2p\,^3P_0$  primary ions with nearly infinite lifetime for the isotope  $^{48}\text{Ti}$  with zero nuclear spin. For the isotope  $^{47}\text{Ti}$  with nonzero nuclear spin hyperfine quenching of these resonances occurs. The procedure for obtaining the associated time constant from a recombination measurement is outlined.

## 1. Introduction

The  $nsnp\,^3P_0$  state in divalent atoms and ions is the first excited state above the  $ns^2\,^1S_0$  ground state. Its decay by a one-photon  $J = 0 \rightarrow J = 0$  transition is strictly forbidden and the lifetime of the  $^3P_0$  state is nearly infinite provided the ion has zero nuclear spin ( $I = 0$ ). If  $I > 0$  the hyperfine interaction mixes levels with different  $J$  and, consequently, the  $^3P_0$  level acquires a finite lifetime. This hyperfine quenching has been treated theoretically for Be-like, Mg-like and Zn-like ions [1, 2, 3, 4]. Theoretical work on neutral alkaline-earth-metal atoms [5, 6] was motivated by the idea to use the hyperfine induced  $^3P_0 \rightarrow ^1S_0$  transition in ultraprecise atomic clocks. In another application the  $^{13}\text{C}^{2+}(^3P_0 \rightarrow ^1S_0)$  fluorescence from planetary nebulae was measured to infer the  $^{13}\text{C}/^{12}\text{C}$  abundance ratio and, thereby, to gain insight into stellar nucleosynthesis [7].

So far, the only experimental values for  $nsnp\,^3P_0 \rightarrow ns^2\,^1S_0$  hyperfine induced (HFI) transition rates were obtained for  $\text{In}^+$  ( $n=5$ ) [8] stored in a radio frequency trap and for Be-like  $\text{N}^{3+}$  from astrophysical observations [9]. Although the latter result had a rather large uncertainty of  $\pm 33\%$ , it allows one to discriminate between the two theoretical values [1, 3] that are available for this ion and that differ by almost a factor of 4. In view of these theoretical uncertainties it is evident that accurate experimental benchmarks are highly desirable, especially for few electron systems such as Be-like ions where correlation effects are particularly strong.

In the present work the hyperfine quenching of the  $2s\,2p\,^3P_0$  state of Be-like  $^{47}\text{Ti}^{18+}$  was observed in dielectronic recombination (DR) experiments carried out at the heavy-ion

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storage-ring TSR of the Max-Planck-Institute for Nuclear Physics in Heidelberg, Germany. The procedure for obtaining the associated decay constant from electron-ion recombination measurements is outlined. The result will be published elsewhere [10]. Here, the  $\text{Ti}^{18+}$  recombination spectrum is presented and its isotope-dependence is discussed.

## 2. Experiment

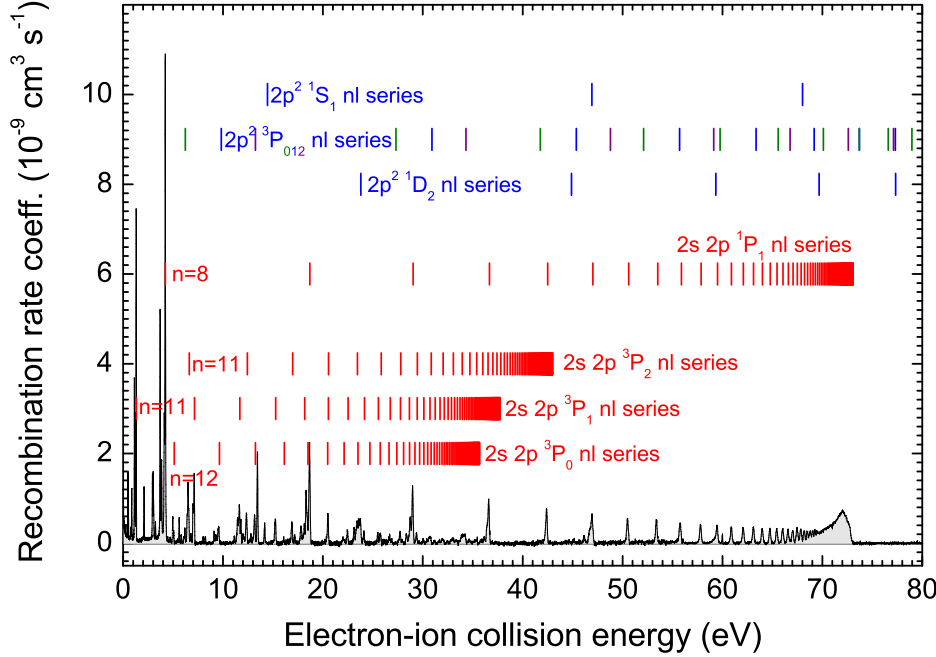
Mass selected  $^{47,48}\text{Ti}^{18+}$  ion beams (natural abundances 7.2% and 73.7%, respectively) were provided by a tandem accelerator, followed by a radio frequency linear accelerator, at energies close to 240 MeV, using a fixed magnetic setting for the beam line and the storage ring. In one straight section of the storage ring the ion beam was continuously phase-space cooled using the velocity-matched electron beam of the TSR electron cooler. In a second straight section, the ion beam was merged with the collinear electron beam of the high-resolution electron target [11], run at variable acceleration voltage in order to set the required collision energy in the co-moving reference frame of the ions. The target electron beam temperatures were  $kT_{\parallel} \approx 40 \mu\text{eV}$  and  $kT_{\perp} \approx 4 \text{ meV}$ .  $\text{Ti}^{17+}$  ions formed by electron-ion recombination in the electron target or by charge transfer in collisions with residual gas molecules were deflected out of the closed orbit of the circulating  $\text{Ti}^{18+}$  ion beam in the first dipole magnet downstream of the electron target and were directed onto a scintillation detector operated in single-particle counting mode with nearly 100% detection efficiency.

Recombination spectra of the  $\text{Ti}^{18+}$  ions as a function of the relative electron-ion energy were taken by varying the cathode voltage of the electron target appropriately. The procedure for electron-ion measurements at the TSR storage ring has been described in more detail in, e.g., Ref. [12] (and references therein). For the present spectral measurements, a constant current of cooled, circulating  $\text{Ti}^{18+}$  ions was maintained. Currents of a fraction of a  $\mu\text{A}$  were injected at a rate of  $\approx 1 \text{ s}^{-1}$  in order to obtain stationary stored currents of  $\approx 40 \mu\text{A}$  for  $^{48}\text{Ti}^{18+}$  and  $\approx 6 \mu\text{A}$  for  $^{47}\text{Ti}^{18+}$ , respectively; this largely reflects the difference in the natural isotope abundances.

## 3. Results and discussion

An overview over the measured  $^{48}\text{Ti}^{18+}$  recombination spectrum is presented in figure 1. The energy range 0–80 eV comprises all resonances associated with  $2s \rightarrow 2p$  ( $\Delta N = 0$ ) core excitations. The spectrum is similar to the previously measured ones of the isoelectronic ions  $\text{Cl}^{13+}$  [14] and  $\text{Fe}^{22+}$  [15]. At higher energies it is dominated by the regular Rydberg series of  $2s^2 \ ^1S_0 \rightarrow (2s\ 2p \ ^1P_1) n\ell$  DR resonances converging to the  $2s\ 2p \ ^1P_1$  series limit at 73.11 eV [13]. The  $2s\ 2p \ ^3P_J$  series limits are barely visible. They are expected to occur at 35.73, 37.77, and 43.05 eV for  $J = 0, 1$ , and  $2$ , respectively. At lower energies the spectrum is more irregular due to the larger fine-structure splitting of the lower- $n$  resonances. Some resonance features, e.g., at 23.6 and 34.0 eV can be related to  $2s^2 \rightarrow 2p^2$  core double-excitations. A thorough discussion of these trielectronic recombination (TR) resonances can be found elsewhere [14].

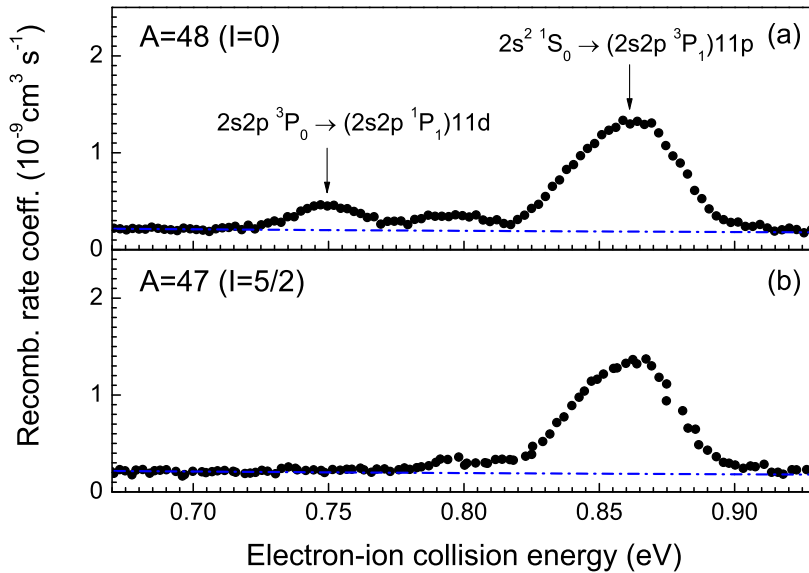
In single-pass merged-beams electron-ion recombination experiments with lower charged Be-like  $\text{C}^{2+}$ ,  $\text{O}^{4+}$ , and  $\text{F}^{5+}$  ions, strong Rydberg series of DR resonances were observed associated with  $2s\ 2p \ ^3P \rightarrow 2s\ 2p \ ^1P$  and  $2s\ 2p \ ^3P \rightarrow 2p^2 \ ^3P$  core excitations of metastable  $2s\ 2p \ ^3P$  primary ions [16]. In these experiments the metastable  $^3P$  fraction in the primary ion beams amounted up to  $\approx 70\%$ . In the present  $^{48}\text{Ti}^{18+}$  recombination spectrum analog strong resonance features are absent. The  $J = 1$  and  $J = 2$  levels of the  $\text{Ti}^{18+}(2s\ 2p \ ^3P)$  term have theoretical lifetimes of 74 ns and 1 ms, respectively [17], much shorter than the average storage lifetime ( $\approx 50 \text{ s}$ ). Thus, the major fraction of the initially present metastable ions decayed to the ground state very fast on the time scale of the experiment, and the remaining (infinitely) long-lived  $^3P_0$  metastable fraction amounted to only  $\approx 5\%$  (see below). In the single-pass experiments, however, typical flight times were of the order of several  $\mu\text{s}$ , i.e., much shorter than the lifetimes of the  $^3P_1$  and  $^3P_2$  states. For lower charged ions these lifetimes are even larger than the values given



**Figure 1.** Measured recombination spectrum of berylliumlike  $^{48}\text{Ti}^{18+}$ . The vertical lines indicate DR resonance positions  $E_n$  for excitation from the  $2s^2 \ ^1S_0$  ground state that were estimated using the Rydberg formula  $E_n = E_\infty - 13.606 \text{ eV} \times (18/n)^2$  with the series limits  $E_\infty$  taken from the NIST atomic spectra data base [13].

above, e.g. 0.16 ms (theoretical value [1]) for the  $\text{F}^{5+}(2s2p \ ^3P_1)$  state, so that even the fastest decaying  $^3P_1$  component of the  $^3P$  term was contained in the primary beams of the single-pass experiments.

In the present experiment DR resonances associated with the excitation of the metastable  $^3P_0$  fraction of the primary ion beam are only observed at low electron-ion collision energies. Figure 2(a) shows a region of the recombination spectrum where resonances of metastable  $^{48}\text{Ti}^{18+}(2s2p \ ^3P_0)$  ions occur close to a strong resonance from ground-state  $\text{Ti}^{18+}$  ions. Theoretical calculations using the AUTOSTRUCTURE code [18] were performed [10] to assign the weaker structures to the metastables. Additionally, the calculations indicate an average



**Figure 2.** Detailed view of DR resonance structures at low energies: (a)  $^{48}\text{Ti}^{18+}$  and (b)  $^{47}\text{Ti}^{18+}$ . The dash-dotted line is the theoretical rate coefficient for nonresonant radiative recombination. Resonances associated with DR of metastable  $^3P_0$  ions are not observed when  $^{47}\text{Ti}^{18+}$  ions with nonzero nuclear spin  $I$  are continuously injected into the storage ring.

population of  $\approx 5\%$  for the metastable  $\text{Ti}^{18+}(2s2p\ ^3P_0)$  ions in the stored  $^{48}\text{Ti}^{18+}$  beam.

Using a  $^{47}\text{Ti}^{18+}$  beam the resonances assigned to metastable  $\text{Ti}^{18+}(2s2p\ ^3P_0)$  ions essentially disappear [Fig. 2(b)]. Their average population is strongly reduced through the  $2s2p\ ^3P_0 \rightarrow 2s^2\ ^1S_0$  HFI radiative decay. The isotope-dependent occurrence of resonances in a DR spectrum was also observed in earlier TSR experiments, using the heavier divalent ion  $\text{Pt}^{48+}$  (Zn-like) [19]. Here, resonances due to  $4s4p\ ^3P_0$  were seen for  $^{194}\text{Pt}^{48+}$  and disappeared for  $^{195}\text{Pt}^{48+}$ . A measurement of the optical decay lifetime, predicted to be 0.2971 ms [20], was not attempted as, in contrast to the present case, it should be much shorter than the time needed for electron cooling of the ion beam. In the present case of  $^{47}\text{Ti}^{18+}$  the theoretical value for the HFI decay rate of the  $^3P_0$  state is  $\tau_{\text{HFI}} = 2.8\text{ s}$  [1] so that a sizeable  $^3P_0$  fraction can be expected in the ion beam even after cooling for some 100 ms.

For the experimental determination of  $\tau_{\text{HFI}}$  the decay of the  $^{47}\text{Ti}^{18+}(^3P_0)$  beam component was monitored as a function of storage time. To this end the relative electron-ion energy in the electron target was set fixed to 0.75 eV where the  $2s2p\ ^3P_0 \rightarrow (2s2p\ ^1P_1)11d$  DR resonance associated with excitation of the  $^3P_0$  state occurs (figure 2). After injection of a single  $\text{Ti}^{18+}$  ion pulse into the storage ring the recombination rate was recorded for up to 200 s. Prior to the injection of the next pulse the remaining ions were kicked out of the ring. This scheme was repeated for a sufficient number of times to reduce statistical uncertainties to a level as low as achievable within one week of beam time. This method had been applied previously for measuring the slow radiative decay rates of  $1s2s\ ^3S$  states in the He-like ions ( $\text{B}^{3+}$ ,  $\text{C}^{4+}$ ,  $\text{N}^{5+}$  [21] and  $\text{Li}^+$  [22]). The experimental result for  $\tau_{\text{HFI}}$  of the  $^{47}\text{Ti}^{18+}(2s2p\ ^3P_0)$  state will be presented and discussed in a forthcoming publication [10].

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